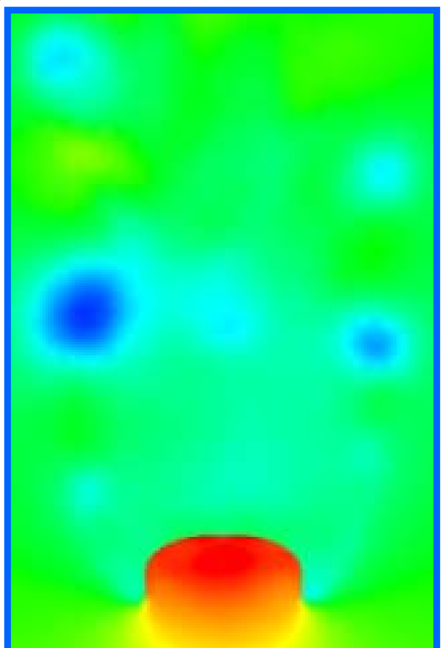
Airdrop Systems Modeling: Methods, Applications, and Validations



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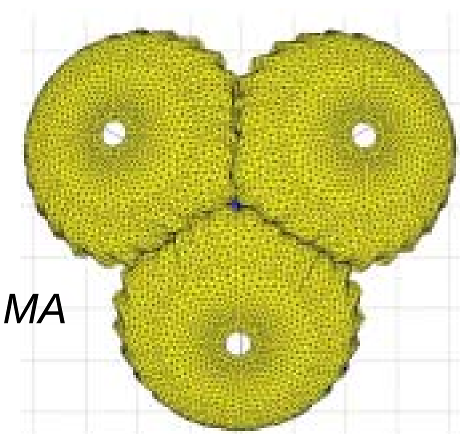

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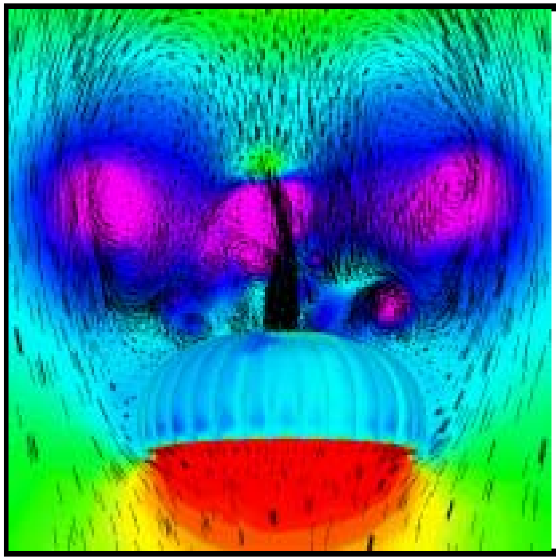
Background: **Motivation**

MOTIVATION:

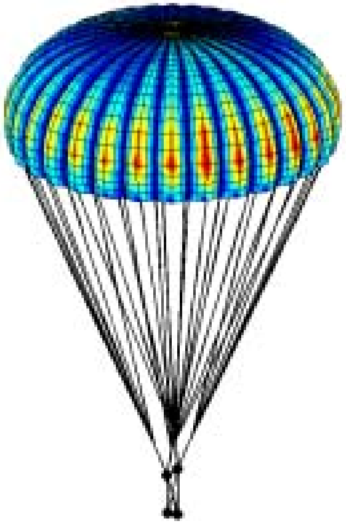
Analytical prediction of parachute performance. Decrease R&D costs and time to fielding new airdrop systems.

APPROACH:

- **Model Fluid-Structure Interaction (FSI)**
- **Numerically couple space-time FEM strategy for fluid with cable-membrane solver for the structure.**



Fluid Dynamics modeling



Structural Dynamics modeling

Outline of Talk

- Background
- Numerical Model
  - Governing equations
  - Finite element formulations
  - Fluid-structure coupling
- Examples
  - Paratrooper and payload separation dynamics
  - Parachute soft-landing simulations
  - Structural modeling
    - Contact phenomena
    - Steering control
  - Validation simulations
- Concluding Remarks

Numerical Model:
Governing Equations

Fluid Dynamics

- **Momentum & Continuity Equations:**

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} + \mathbf{f}\right) - \nabla\cdot\boldsymbol{\sigma} = 0 \quad \text{on } \Omega_t,$$
$$\nabla\cdot\mathbf{u} = 0 \quad \text{on } \Omega_t.$$

- **Constitutive Equations:**

$$\boldsymbol{\sigma}(\mathbf{u}, p) = -p\mathbf{I} + 2\mu\boldsymbol{\varepsilon}(\mathbf{u})$$
$$\boldsymbol{\varepsilon}(\mathbf{u}) = \frac{1}{2}\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right).$$

- **Boundary and Initial Conditions:**

$$\mathbf{u} = \mathbf{g} \quad \text{on } (\Gamma_t)_g\,,$$
$$\mathbf{n}\cdot\boldsymbol{\sigma} = \mathbf{h} \quad \text{on } (\Gamma_t)_h.$$
$$\mathbf{u}(\mathbf{x}, 0) = \mathbf{u}_0.$$

Structural Dynamics

- **Conservation of Linear Momentum:**

$$\rho^s\left(\frac{d^2\mathbf{y}}{dt^2} - \mathbf{f}^s\right) - \nabla\cdot\boldsymbol{\sigma}^s = 0 \quad \text{on } \Omega_t^s$$

- **Constitutive Equations:**

Membrane:

$$S^{ij} = \left(\bar{\lambda}_m G^{ij}G^{kl} + \mu_m\left[G^{il}G^{jk} + G^{ik}G^{jl}\right]\right)E_{kl}$$

Cable:

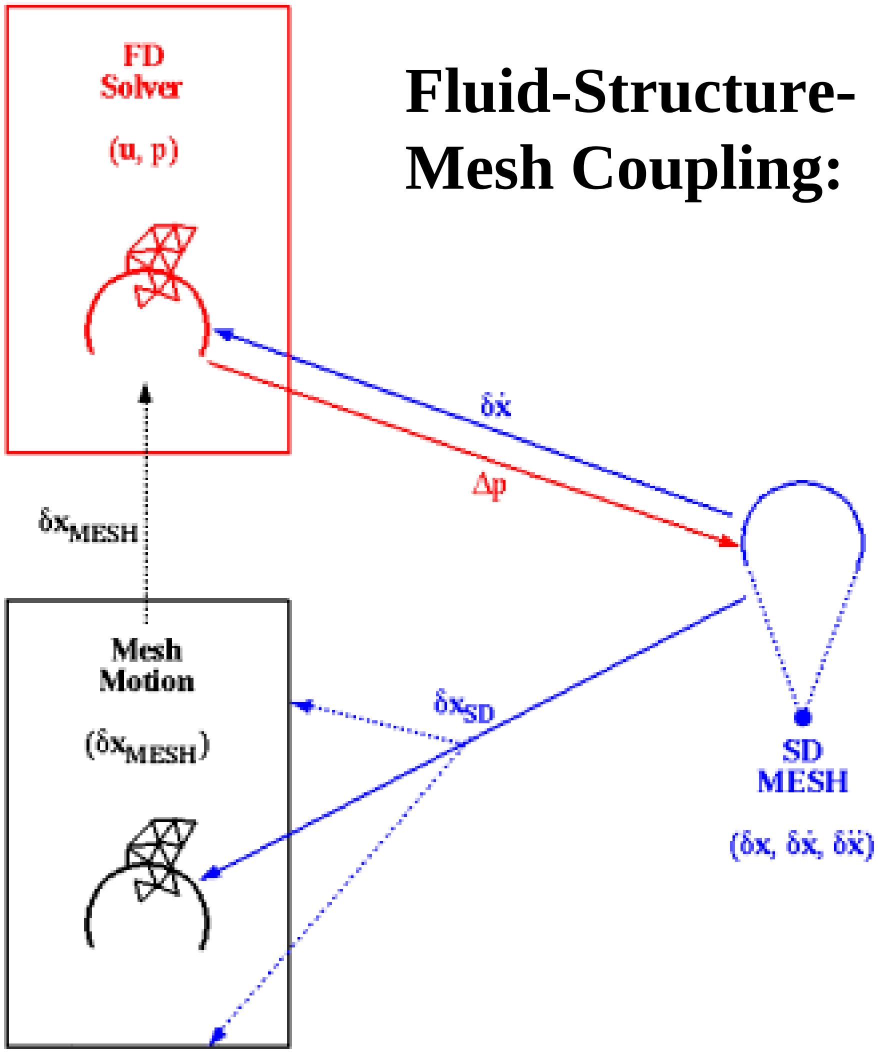
$$S^{11} = E_c G^{11} G^{11} E_{11}$$

Numerical Model:
Finite Element Formulations

- **Fixed boundary problems**
  - Stabilized semi-discrete finite element formulation of incompressible Navier-Stokes equations (Tezduyar, 1991)
- **Moving boundary problems**
  - Stabilized "space-time" finite element (DSD/SST) formulation (Tezduyar et. al, 1994)
- **Parachute fluid-structure interaction problems**
  - DSD/SST formulation for fluid dynamics
  - Cable-Membrane parachute structural model (Leonard and Benney, 1995)
  - Automatic mesh update strategy

Numerical Model:
Fluid-Structure Coupling:

Fluid-Structure-Mesh Coupling:



- **Timestep loop**
  - **FSI loop**

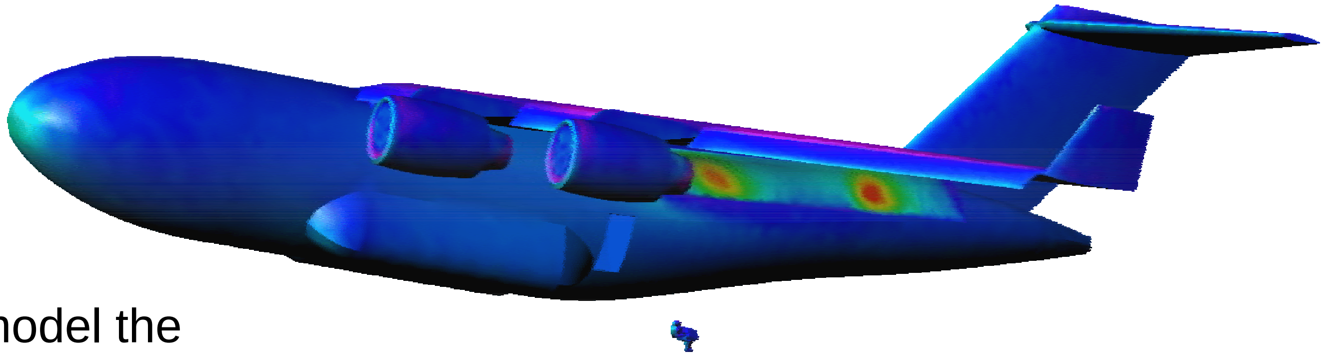
    SD solver:
    - *Obtain pressures from FD*
    - *Newton-Raphson update for SD*

    Mesh Motion:
    - *Obtain displacements from SD*
    - *Mesh Motion*

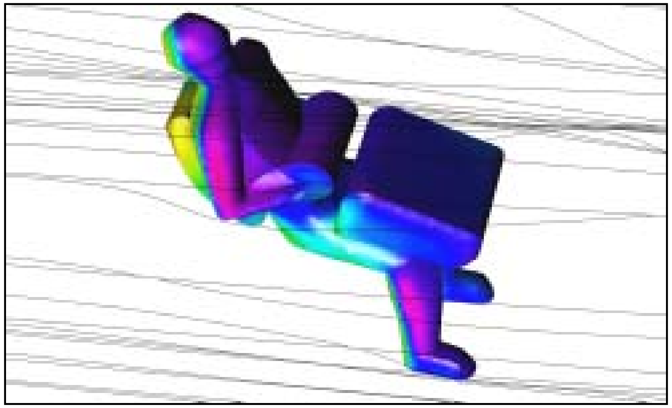
    FD solver:
    - *Obtain velocities from SD*
    - *Newton-Raphson update for FD*

  Repeat until converged

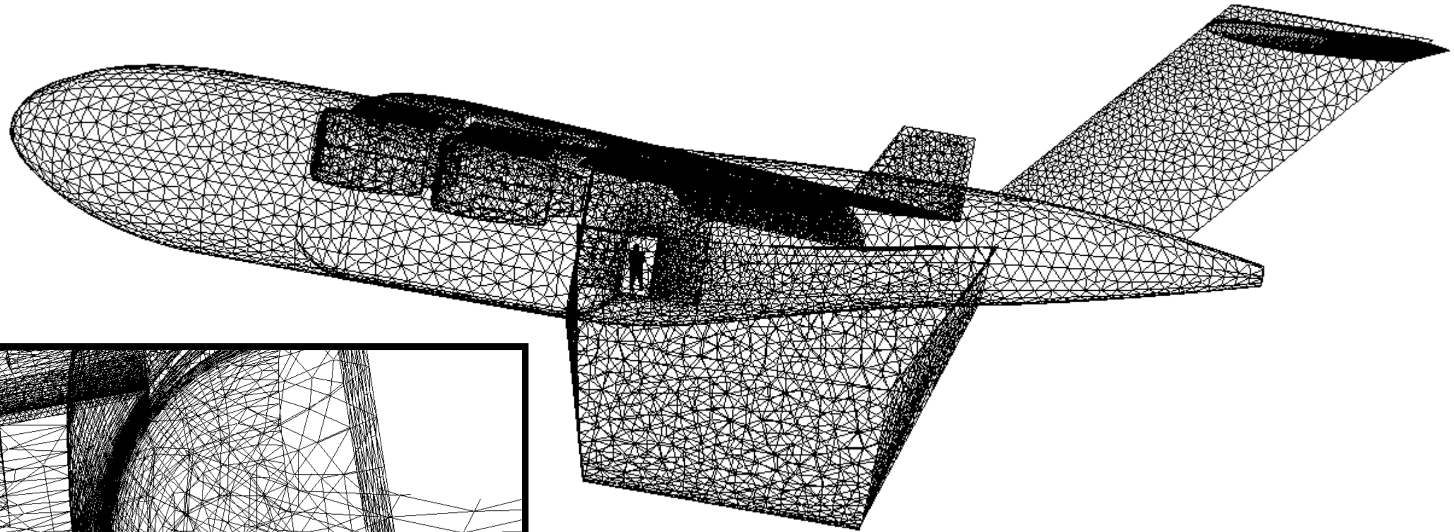
Example -
Paratrooper and payload separation dynamics

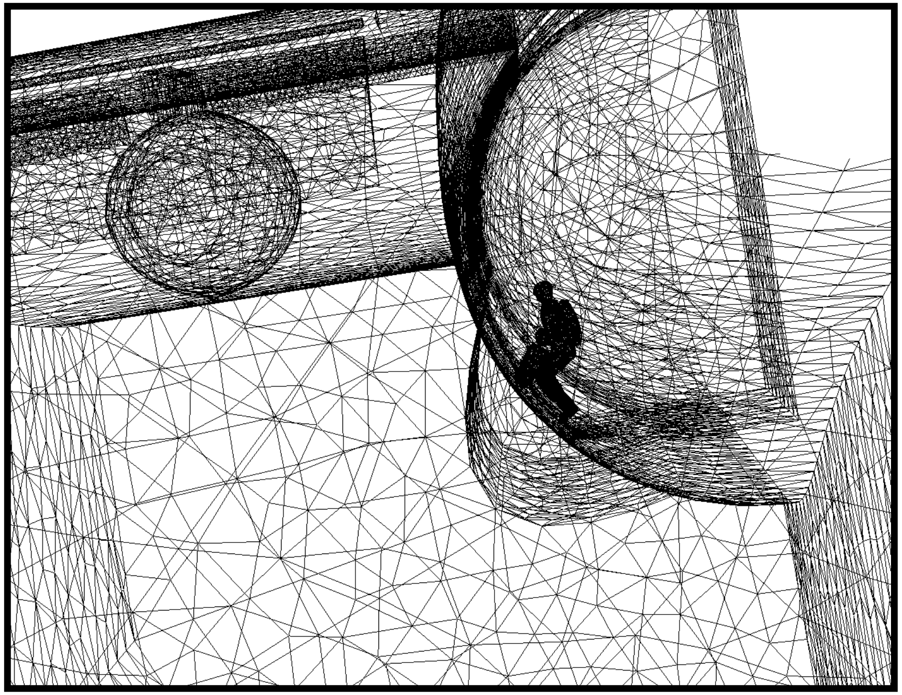


- **Purpose**
  - To accurately model the aerodynamic interaction between aircraft and paratrooper or cargo.
- **Numerical Method**
  - Path of paratrooper (or cargo) influenced by aircraft flow field.
  - DSD/SST method used to handle time-variant spatial domains.
  - Changes in paratrooper (or cargo) orientation and relative position to aircraft handled with automatic mesh moving method.
  - Occasional remeshing.



Example -
Paratrooper and payload separation dynamics





Plane and Paratrooper Surface Mesh with Remeshing Box

Volume Mesh
- Paratrooper (106,264 nodes, 602,061 elements)
- Cargo (289,838 nodes, 1,697,658 elements)

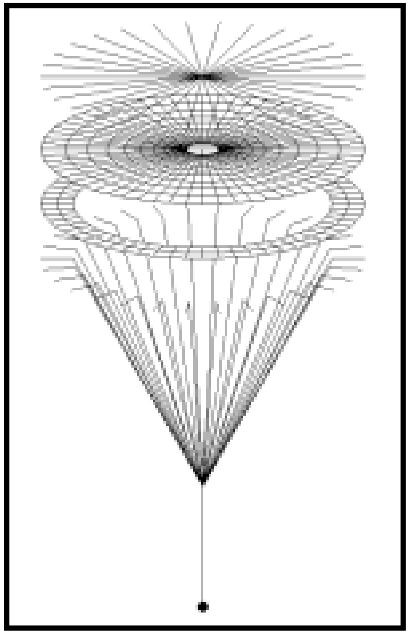
Example -
Parachute soft-landing simulations

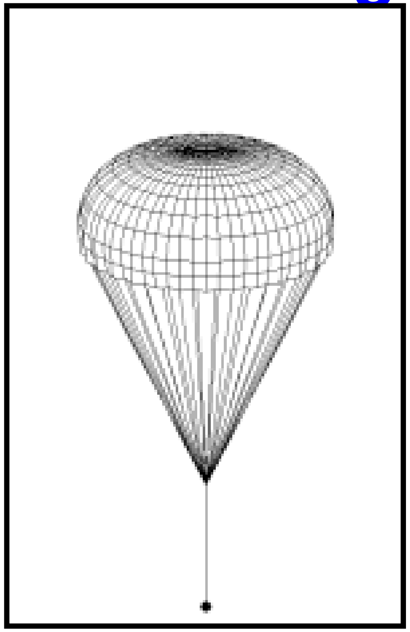
- **Motivation**
  - Payload retraction systems are a possible solution for Army soft-landing airdrop needs.
- **Approach**
  - Modeling of fluid-structure interaction (FSI)
- **Problem Definitions**
  - T-10 parachute
  - System weight: 300 lbs
  - 14 ft PMA
    - 38% retraction
    - 0.14, 0.21, 0.28 s retractions

(1/5 second between frames)

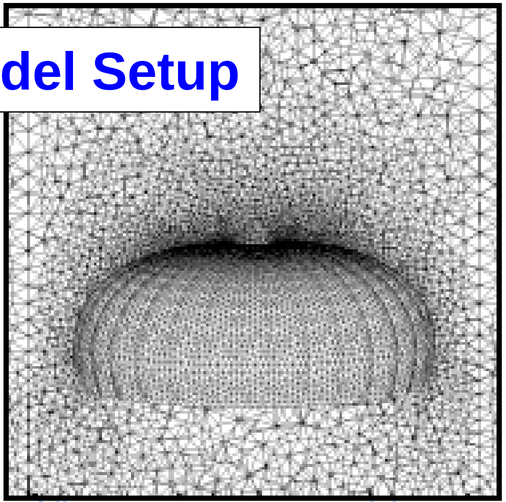
Example -
Parachute soft-landing simulations

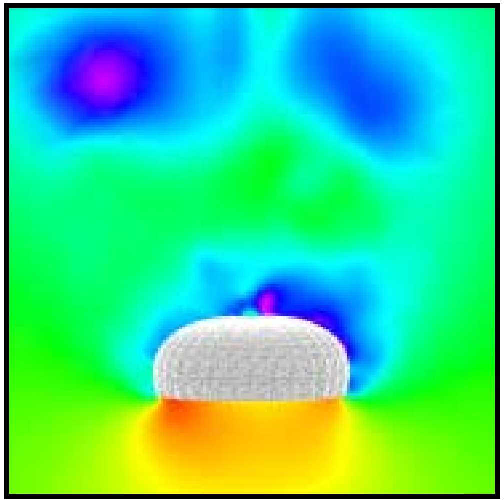
SD Model Setup





FD Model Setup

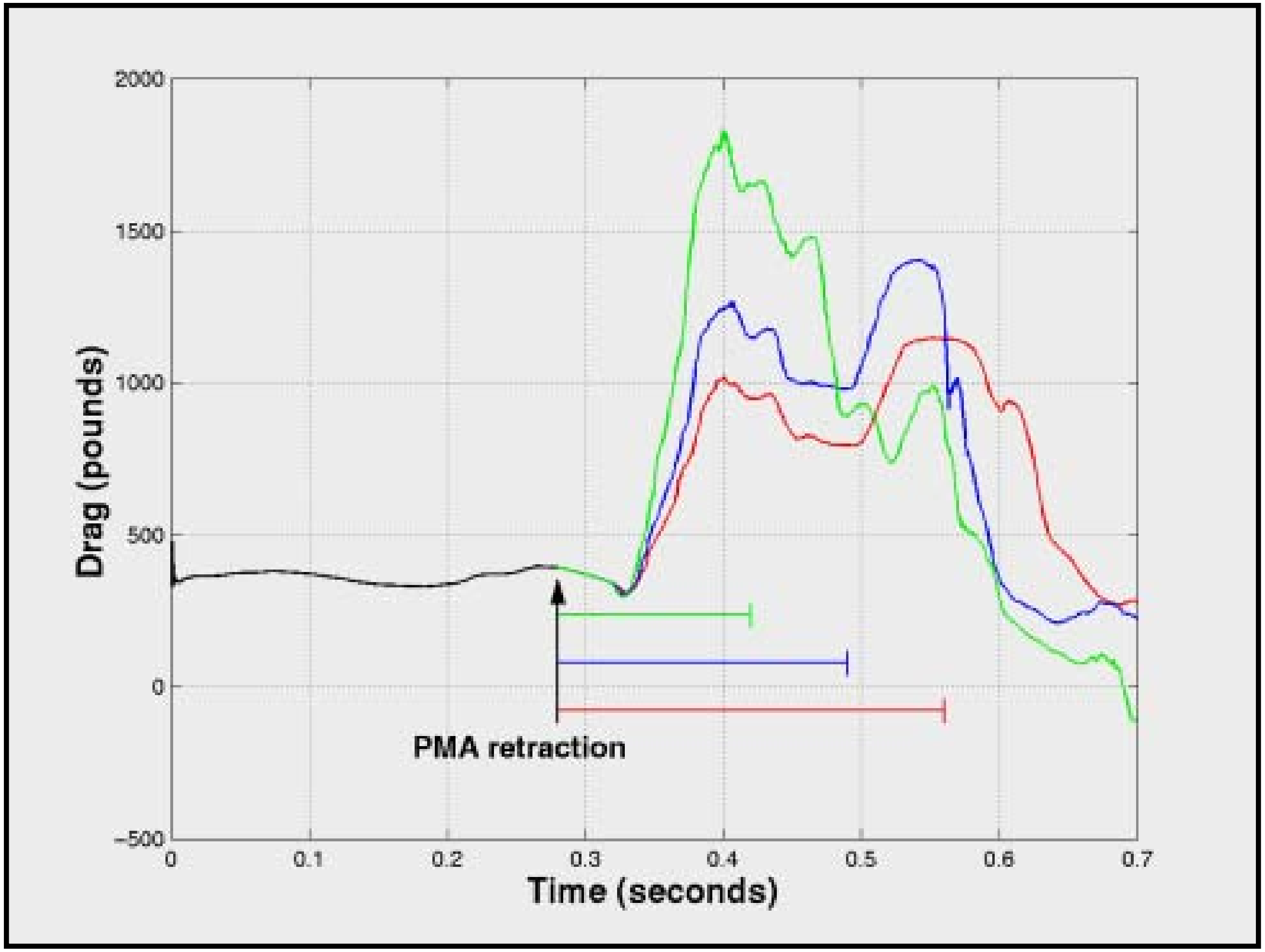




FSI Simulation

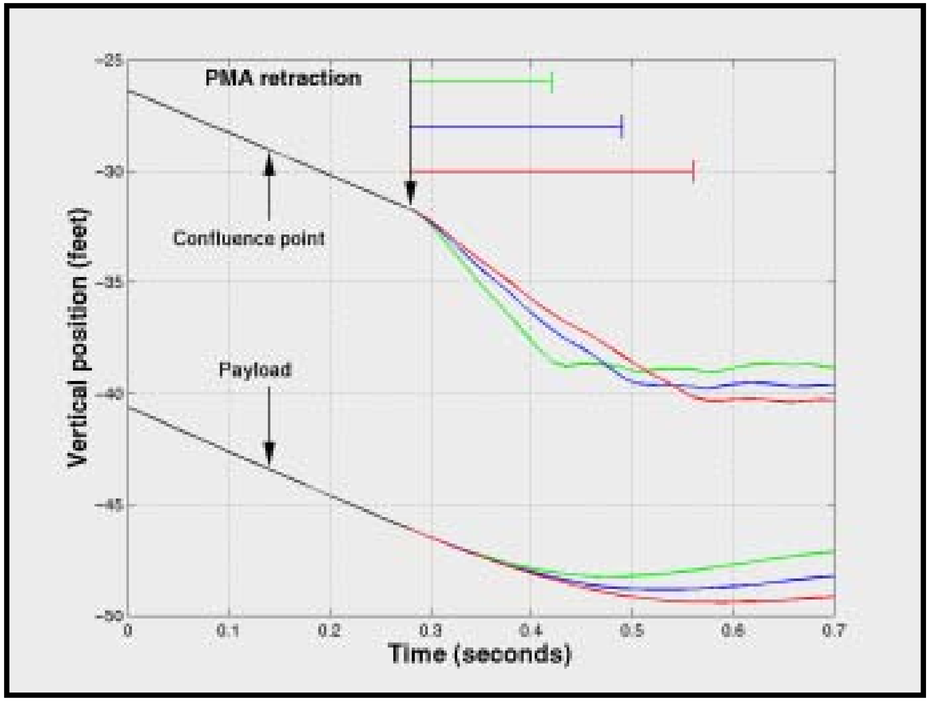
Example - Parachute soft-landing simulations

Aerodynamic Drag

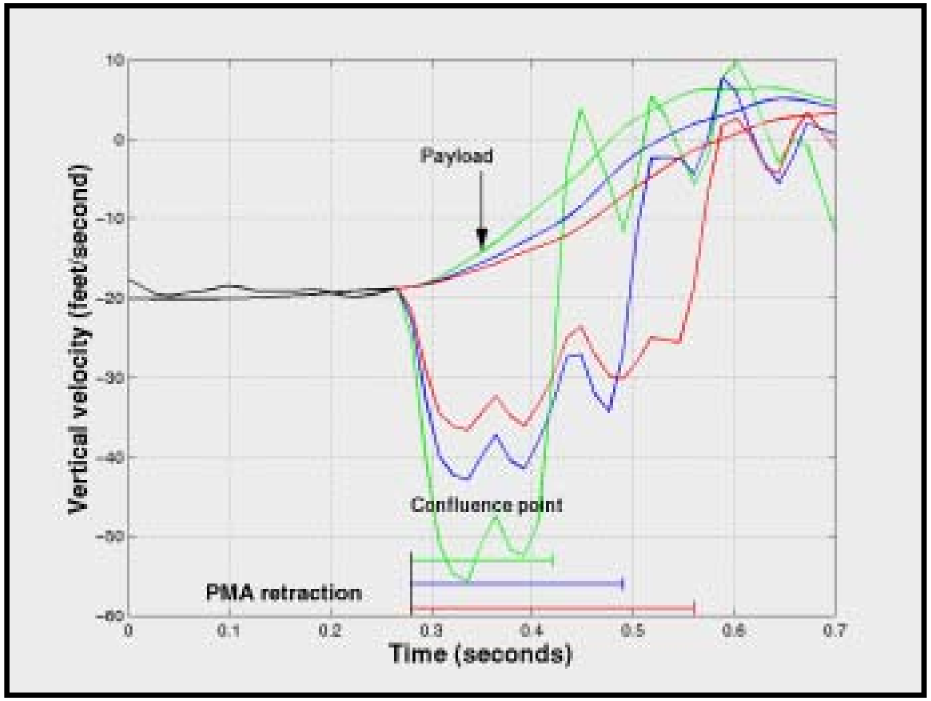


Example -
Parachute soft-landing simulations

Position



Velocity



Example - Structural modeling: Contact analysis

Contact Search & Projection Algorithm

- Automatic (i.e. No User Input)
- Broadcast Nodal Displacements to all Processors

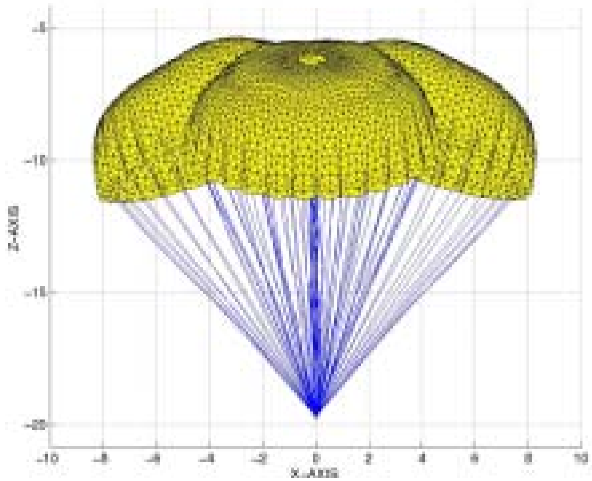
Contact Mechanics

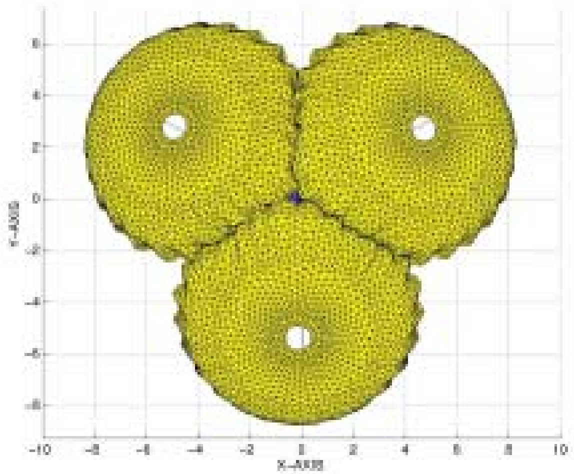
- Lumped Contact Stiffness for Implicit Integration
  - **Dominant Term is Similar to a Mass Matrix**
  - **Eliminates Contact Connectivity Problem**
  - **Improves Diagonal Dominance**

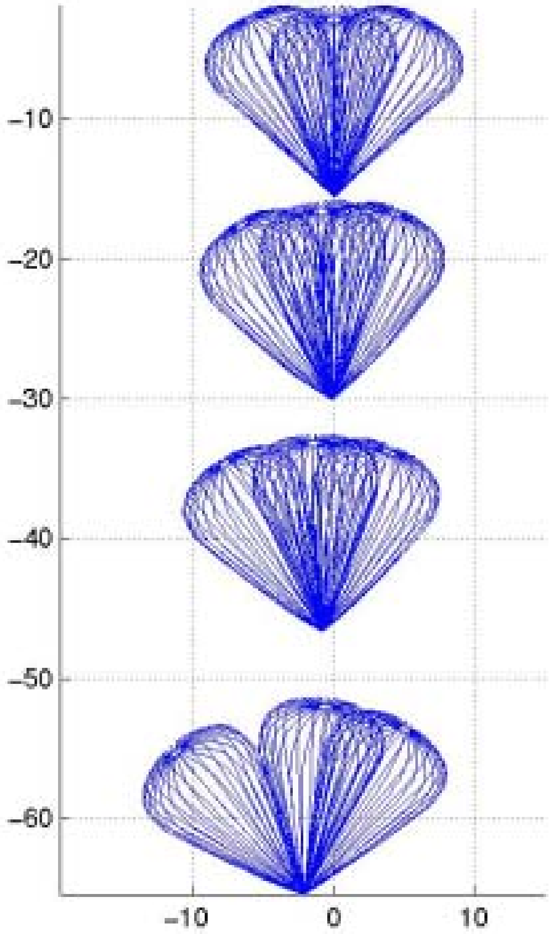
Contact Constraints

- Penalty Method

Example -
Structural modeling: Contact analysis

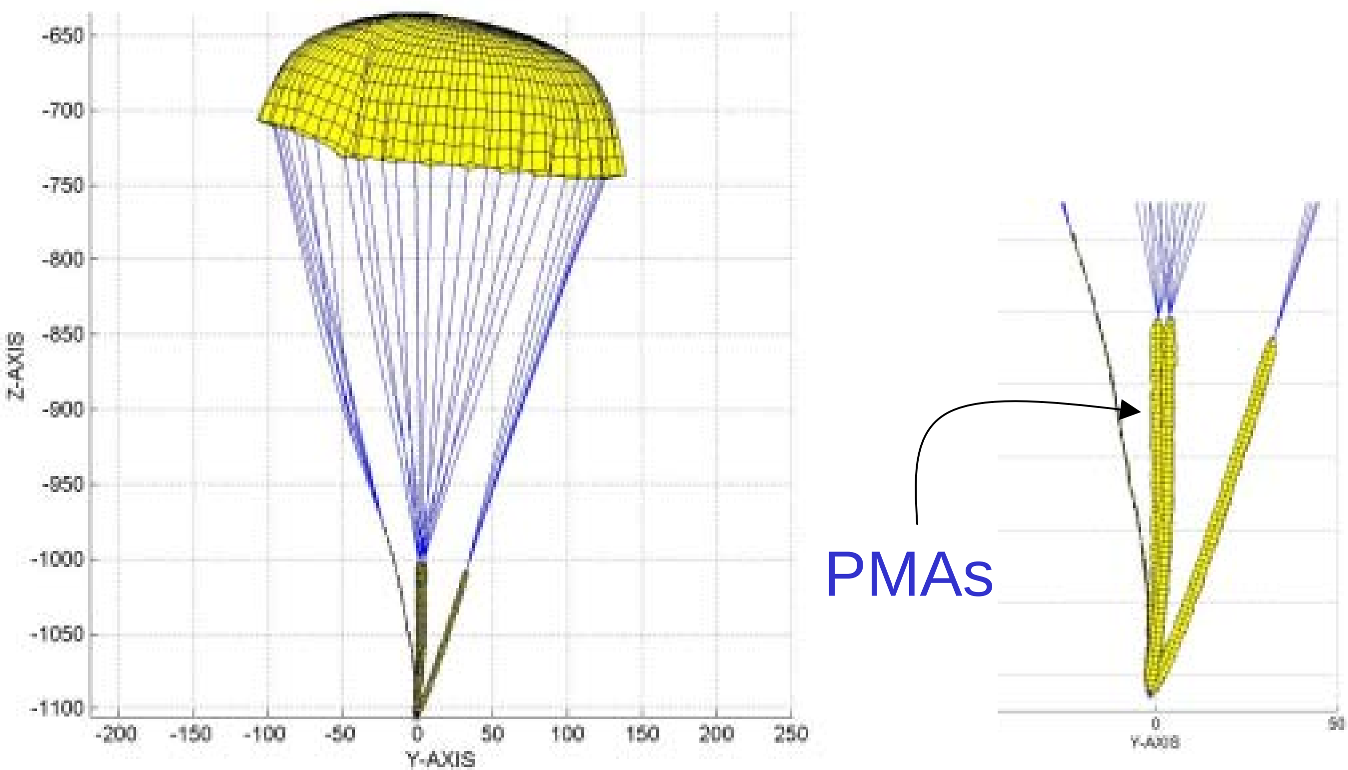






Example -
Structural modeling: Simulations of parachute system steering control

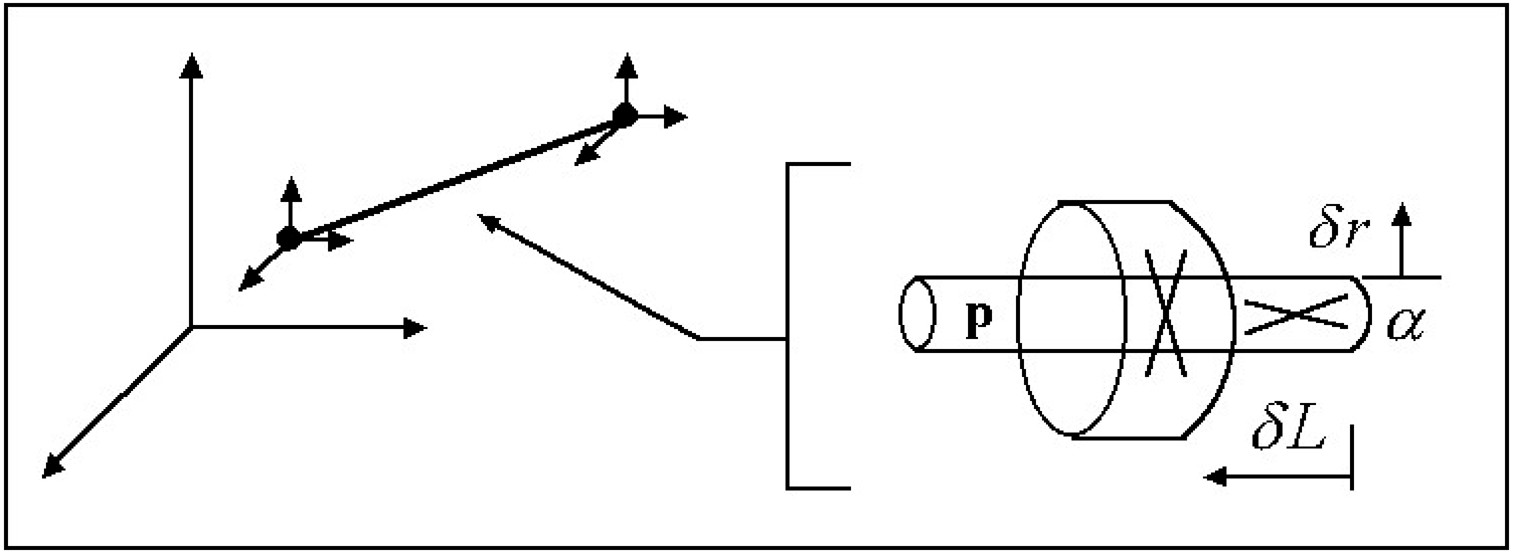
Old Method: PMA = GNL Anisotropic Membranes



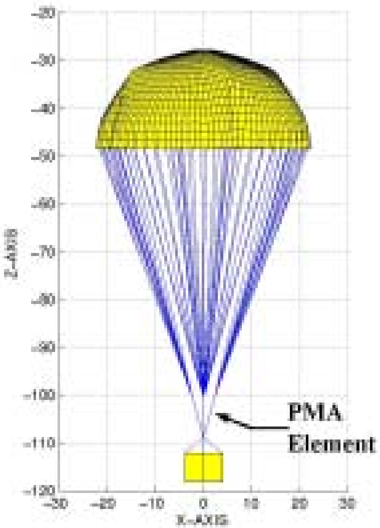
Example - Structural modeling: Simulations of parachute system steering control

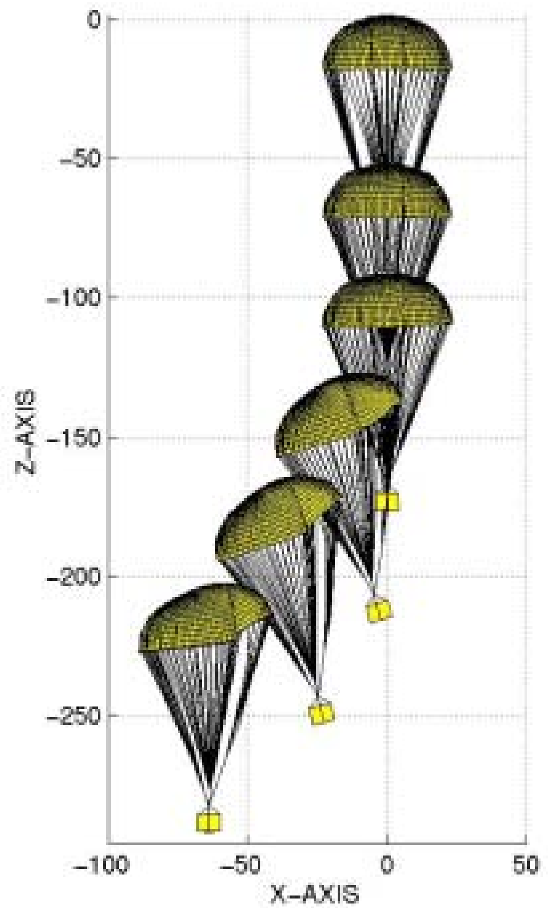
New Method: PMA Element

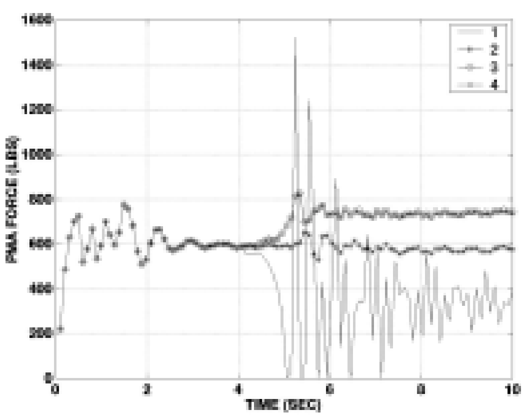
- **GNL, 2 Node, 6 DOF, 1D Element**
- **Inextensible Fiber Kinematics**
- **Include Pressure & Kinematics in PVW**
- **Assume Everything is Constant Along Element Length**
- **Yields Correct Relation between PMA Pressure, Length, & Force**



Example -
Structural modeling: Simulations of parachute system steering control





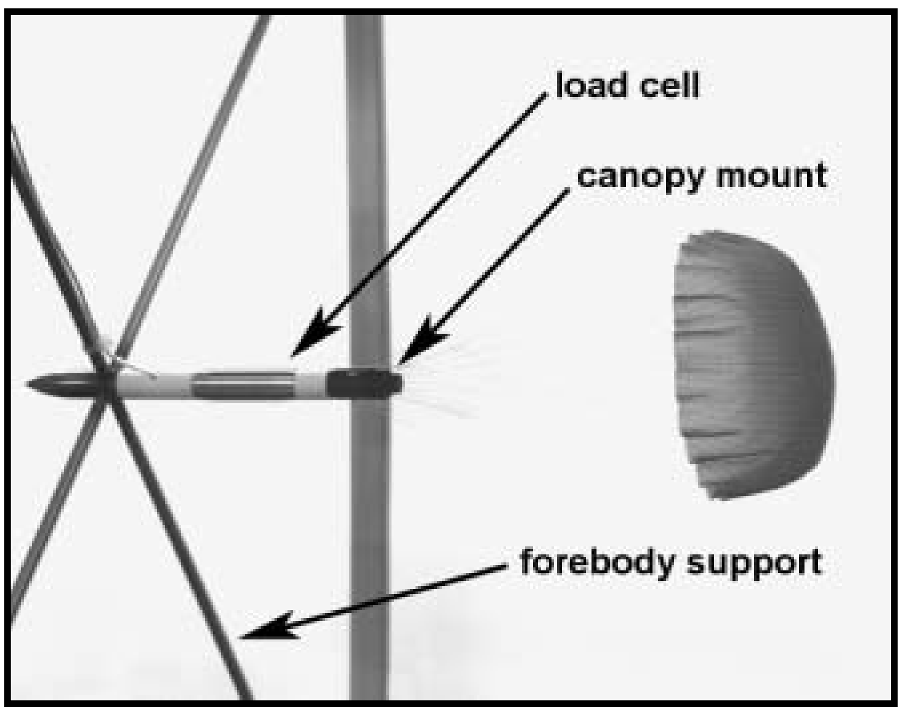


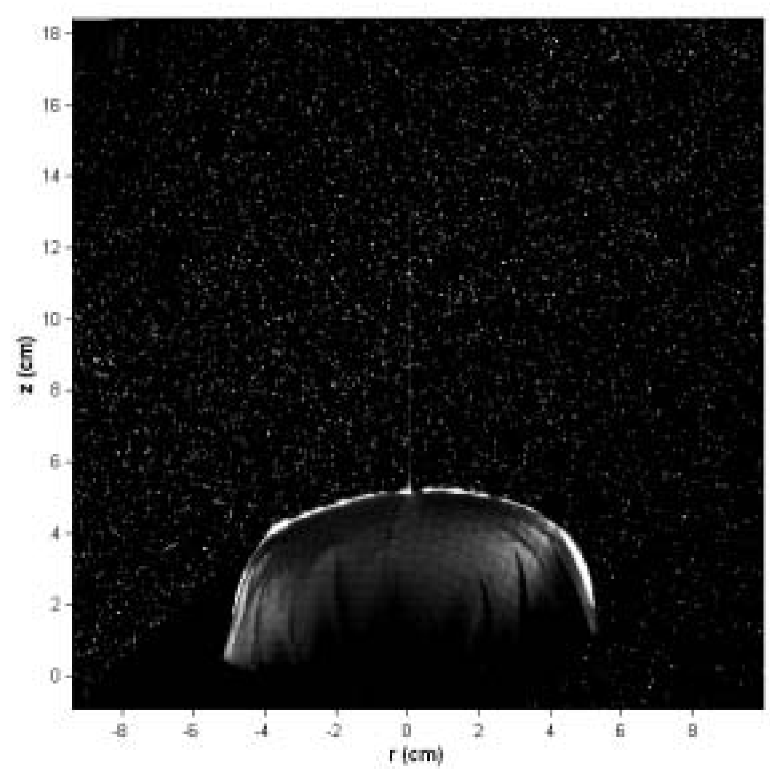
Example - Validation simulations

- **Previous work**
  - Steady state and starting flow about a rigid, generic parachute canopy (Johari et al., 2001)
  - FSI computations of T-10 and scaled cross parachutes (Stein et al., 1999, 2000, 2001)
  - Reasonable agreement between FSI results and the experiments (drag and surface pressure at several points)
  - Difficult to validate the simulations due to the lack of detailed measurements for full-scale canopies

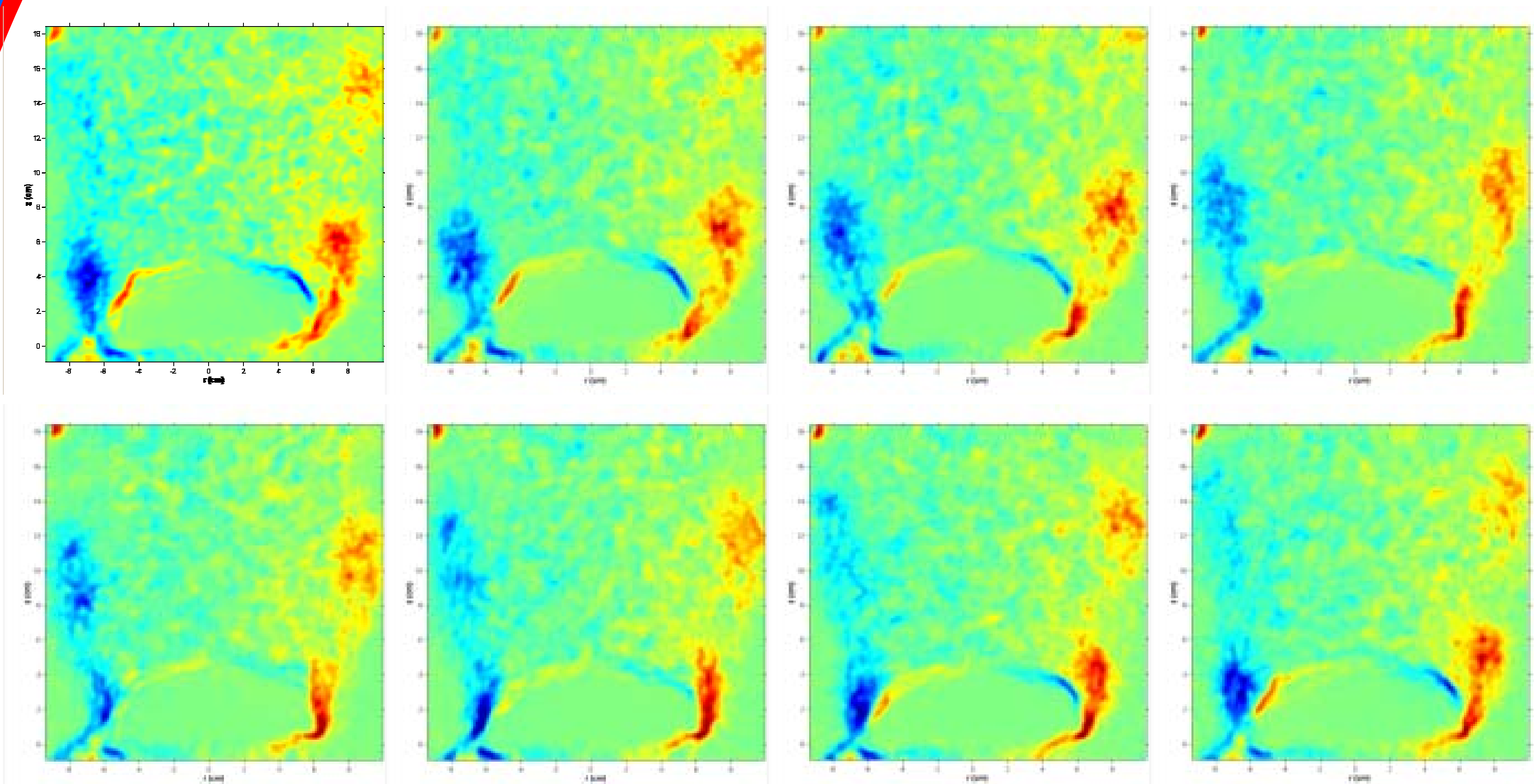
Example - Validation simulations

- **Experimental Setting**
  - 15-cm circular canopy in a horizontal water tunnel
  - Freestream velocity of 20 cm/s, Re =3×10^4
  - Canopy geometry, drag, and velocity field measurements

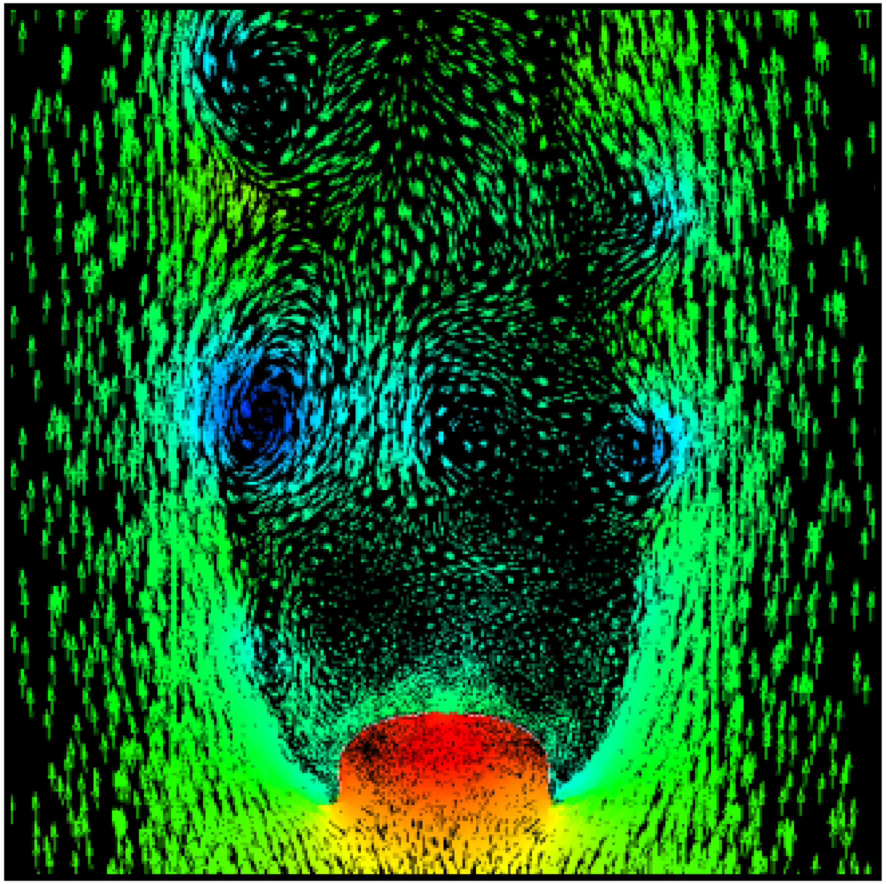


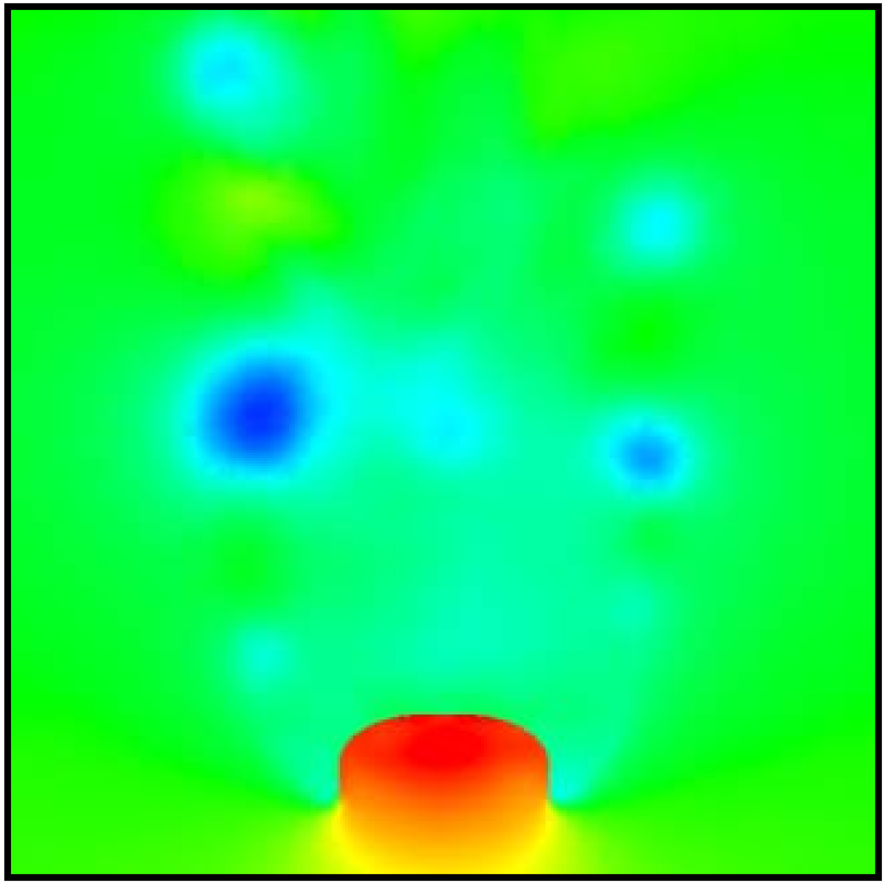


Example -
Validation simulations: Phase-Averaged Vorticity Field



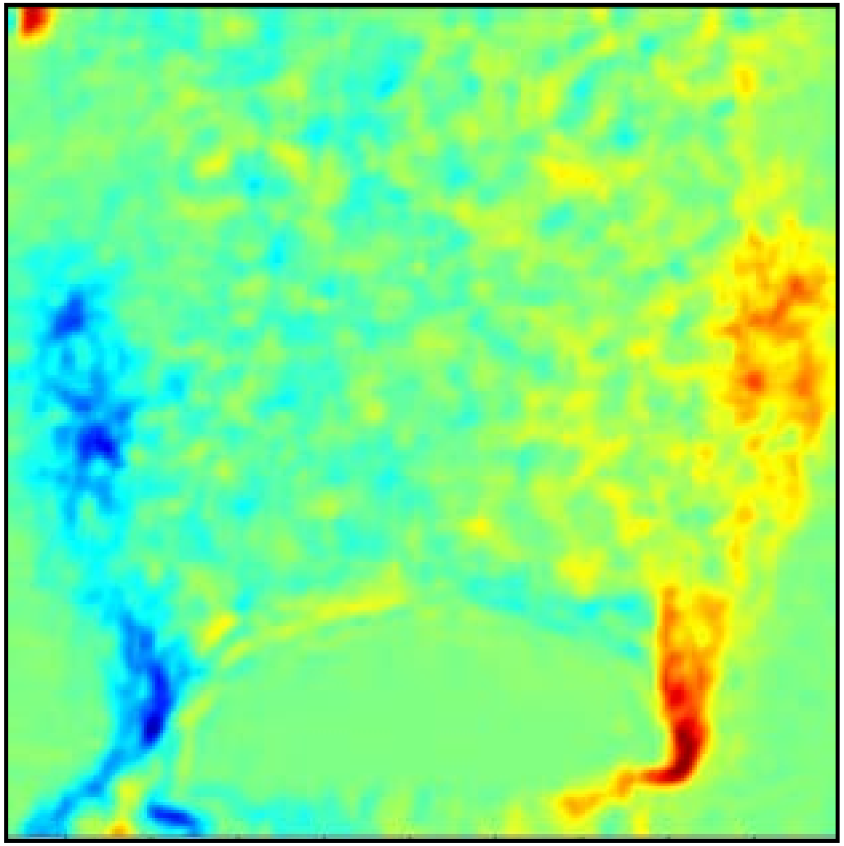
Example - Validation simulations: Computed flow field



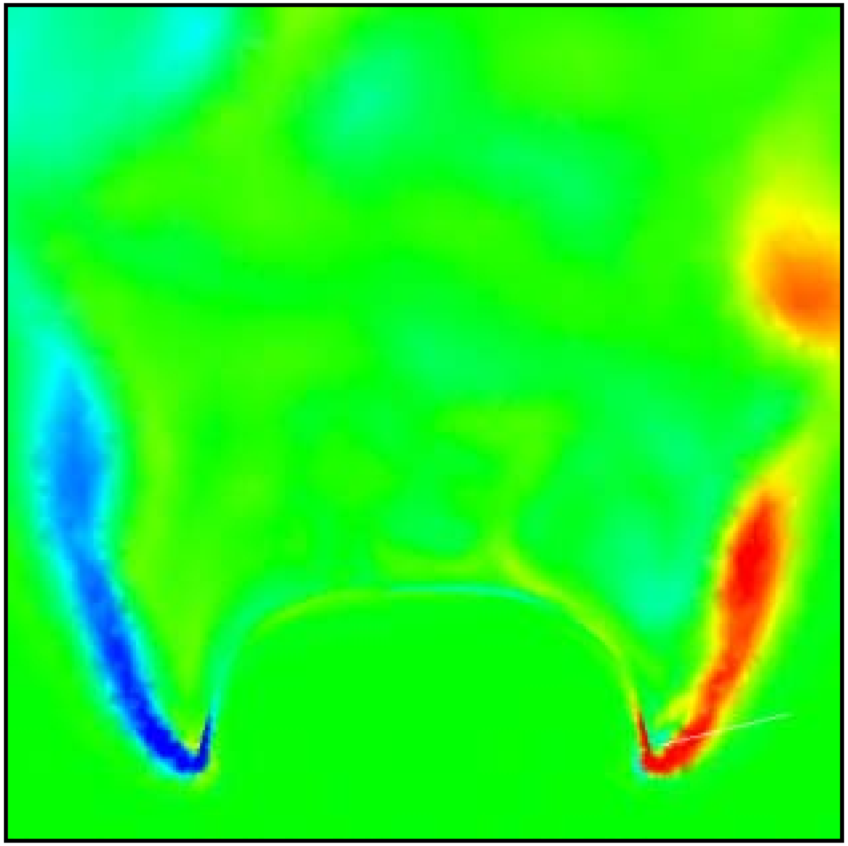


Example -
Validation simulations: Vorticity field

Experiment (PIV)



FSI Simulation



Concluding Remarks

- **Numerical methods are being developed to advance airdrop systems modeling capabilities**
- **These methods have been demonstrated for a few application simulations and test problems:**
  - Initial paratrooper/payload separation from delivery aircraft
  - Fluid-Structure Interactions for parachute soft-landing systems
  - Structural modeling methods for parachute contact analysis and parachute steering controls
  - Validation simulation and experiments
- **Ongoing and future directions:**
  - Further enhancement of model
  - **Airdrop application simulations**